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PROPERTIES OF HONEYCOMB CORES AS AFFECTED BY FIBER TYPE, FIBER ORIENTATION, RESIN TYPE, AND AMOUNT

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Forest Products Laboratory

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SUMMARY

The present investigation was conducted to determine the effect of fiber type, fiber orientation, resin type, and resin content on the strength properties of honeycomb core structures. The structures examined were made from nonwoven cotton, nonwoven rayon, and paper. Some cores had the principal fiber grain parallel to and others had it perpendicular to the cells of the honeycomb. One or more resins in varying amounts were used to impregnate or bond the three materials.

Structures made from paper had considerably greater tensile, compression, and shear strengths than cores made from either cotton or rayon. Higher tension and compression strengths were obtained with honeycomb structures in which the principal fiber grain was parallel to rather than perpendicular to the axes of the cells. Honeycomb structures made from each of the three fiber materials retained more than 75 percent of their dry tensile strength after complete saturation in water. Cotton retained a higher percentage of its strength upon wetting than paper, and rayon retained the least.

In general, the highest strength values (adjusted to a common specific gravity) were obtained from structures in which the pretreated corrugated sheets were held together with a small amount of a phenolic adhesive and the assembled core was saturated with an alcohol-soluble phenolic resin. The effect of increases in pretreating-resin content on the increase in strength properties was more noticeable for structures tested in the water-soaked than in the dry condition.

INTRODUCTION

The sandwich panel, because of its very high stiffness per unit of weight, has been an attractive material for consideration by designers

of modern high-speed aircraft. A structural panel of this kind can be made by bonding strong, stiff, and thin facing materials to each side of an appreciable thickness of a low-density core. The function of the core is to space mechanically and to stabilize elastically the facings when they are highly stressed.

A core material should be light in weight, uniform, capable of being formed or cut to close tolerances, and suitable for subsequent bonding to facings. Its important mechanical properties include sufficient tensile strength, compressive strength, and modulus of elasticity in the direction perpendicular to the plane of the facings, shear strength and modulus of rigidity in planes perpendicular to the facings, and impact resistance. High inherent strength is desirable in that it usually permits a minimum weight to be realized. Other characteristics that are important but that may vary considerably from one material to another are maintenance of strength at high or low temperatures, thermal or dielectric properties, resistance to aircraft liquids, decay organisms, and water, and maintenance of strength upon thorough wetting.

Materials that have been evaluated for suitability according to the above criteria include balsa wood, foamed cellulose acetate, rubber, or plastics, and formed, corrugated, or expanded paper, fiber mats, metallic foils, or woven sheets of glass fibers or cotton. Thermoplastic and thermosetting resins have been used alone in the foamed form, or as bonding agents or saturants for sheet materials.

From a consideration of the requirements for strength, light weight, availability, and resistance to liquids and temperatures, core structures made of fiber sheet materials reinforced with thermosetting resins are certainly among the most promising. The fiber is the principal strength-giving component, and considerable latitude exists in obtaining predetermined degrees of fiber orientation and in utilizing a predominant fiber direction to the best advantage.

The present investigation was undertaken to determine the relationships between various strength properties of honeycomb core structures made from nonwoven or felted fiber webs and representing various conditions of fiber type, fiber orientation, resin type, and resin content. Special consideration was given to the factors involved in attaining high tensile strength normal to the facings. High-strength papers with a moderate degree of fiber orientation and nonwoven rayon and cotton webs of very high fiber orientation were selected as convenient base materials for studies of the variables. The base sheet material was impregnated with one or more resins in varying amounts, and, following corrugation, sheets were assembled into honeycomb structures having the predominant fiber grain in either of the two directions. Tests

included determination of the physical properties and equilibrium moisture content of the base sheet material and the determination of tensile and compressive strengths in the wet and dry conditions and shear strength in the dry condition of honeycomb structures. Strength values were adjusted mathematically to give comparative data at a constant density to permit an analysis of the effects of composition and fiber orientation.

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PREPARATION OF BASE SHEET MATERIAL

Fibrous Material, Resins, and Adhesives

A nonwoven rayon sheet and a nonwoven cotton sheet, each having a weight of 45 pounds per 3000 square feet and neutral kraft-base paper of 40 and 110 pounds per 3000 square feet were selected as the basic fibrous materials for these experiments. A commercial water-soluble phenolic resin was used as an impregnant for the paper. The following types of resins or adhesives were used for assembly of sheets into the cores: (A) A high-temperature-setting, low-viscosity, laminating resin of the polyester type, (B) an intermediate-temperature-setting phenolic resin containing 6 percent of an acid catalyst, and (C) the same as (B) plus an additional treatment with a commercial alcohol-soluble phenolic saturating resin.

Partial Impregnation of Base Sheet Material

The cotton, rayon, and paper were treated on an experimental resin-impregnating machine. Nominal water-soluble phenolic resin contents of 2.5, 5, 7.5, 10, 20, and 30 percent were obtained on the 40-pound paper and of 20 percent on the 110-pound paper, nonwoven cotton, and rayon. The resin content is based on the difference in weight between the untreated sheet and the treated sheet, corrected for volatile content, as both emerge from the drying tower of the impregnator, and it is expressed as a percentage of the weight when treated. The temperature of the tower was about 140° C (284° F) at the center, and the speed of the sheet through the 12-foot tower was approximately $4\frac{1}{2}$ feet per minute. Under these conditions the volatile content of the sheet was between 3 and 6 percent. This value is based on the volatile loss

during a 10-minute exposure in an oven at 160° C (320° F), and it is expressed as a percentage of the original weight of the treated sheet. The resin was diluted with a 50-50 mixture of water and ethyl alcohol.

To determine the effects of the different saturating resins on the rate and permanent affinity for moisture of the fiber itself, as well as on the strength properties of the fibrous sheet, special 12- by 12-inch sheets were prepared by hand-dipping sheets in solutions of water-soluble, alcohol-soluble, and polyester resin. The concentration of each solution was chosen so that a resin content of 30 percent resulted in the sheet after cure of the resin.

Corrugating

The impregnated materials were corrugated on a commercial machine equipped with B-size flute rolls. The speed of the corrugator was approximately 15 feet per minute, and a steam pressure of about 90 psi was used in the rolls. Corrugated materials were prepared in which the flutes of the corrugations were either perpendicular or parallel to the predominant fiber direction of the material. To produce material with the flutes perpendicular to the fiber direction (T-direction, fig. 1), the material was passed through the corrugator directly from the roll. Sheets were cut by hand into 3-foot lengths and nested immediately. In order to produce material with flutes parallel to the predominant fiber direction (L-direction, fig. 1), 12-inch-square sheets of the material were passed through the corrugator so that the fiber direction was perpendicular to the direction of the movement through the corrugating machine. No attempt was made to cure the resin in the material during corrugating.

Cure of Saturating Resin

Packs of the corrugated material about 3 inches thick were placed in a circulating-air type of oven at a temperature of 125° C (257° F) for about 4 hours for partially curing the resin. The increased stiffness of the flutes that resulted from this cure was an aid to subsequent handling.

To obtain physical properties of the treated base sheet materials, it was necessary to cure a number of the uncorrugated sheets. Sheets 12 inches square were subjected to 163° C (325° F) for 5 minutes. This was done without pressure on the platens of a hot press.

PREPARATION OF CORES

Gluing of Corrugated Material and Curing of Cores

Blocks of honeycomb core material were made by using three different resins or resin combinations, as shown in table 1. Resin treatment A consisted of spreading a uniform film of a high-temperature-setting polyester type of laminating resin on a level plane surface with a doctor blade (fig. 2). The adjustment of the clearance between the surface and the edge of the doctor blade controlled the resin content. The corrugated sheets were placed on the resin film, so that the resin was transferred to the crests of the corrugated material. A slight pressure was used to insure adequate contact of the material with the resin. A short time interval was given to permit sufficient penetration of the resin into the material. The thickness of the resin film was adjusted so that enough resin was applied to the crests to yield an assembled core having a resin content (after cure) of approximately 52 percent (based on the weight of the treated core) for cores made with paper and of 70 percent for cores made with rayon or cotton. This resin penetrated into the material, and the large amount was necessary to produce a satisfactory crest-to-crest bond. The cores made with this adhesive and procedure in earlier work yielded structures having high compressive strength.

To produce low-density structures with a high percentage of fiber, which was believed to be the tensile-strength-producing component, honeycomb structures were fabricated by using a low-resin-content base sheet and a hot-setting phenolic adhesive to supply the crest-to-crest bond required (resin treatment B). This adhesive was applied to the crests of the corrugated sheets by using a small hand-driven glue spreader, as shown in figure 3. The adhesive was used as received, at 60 percent solids content, and the spread was adjusted to give an application of about 1.2 grams of solid glue per square foot. This glue did not penetrate far into the material. The sheets of corrugated materials were passed through the glue spreader with the flute direction parallel to the axis of the spreader roll.

The treated corrugated material was assembled into cores by placing layers of the corrugated material so that the crests of each ply made contact with the crests of adjacent plies. Short sections of paper straws were placed at the four corners of each sheet to serve as keys to maintain the alinement of the corrugations. In addition, a jig with strip heaters (fig. 4) was used to tack the resin at the ends of the flutes and to maintain the crest-to-crest alinement. Core blocks 4 feet long, 1 foot wide, and $2\frac{1}{2}$ inches thick were produced from the material having the corrugated flutes perpendicular to the fiber

direction. Blocks 12 inches long, 9 inches wide, and $2\frac{1}{2}$ inches thick were made from the material having the flutes parallel to the fiber direction. The core blocks were placed between parallel cauls, and the assembly was placed in a circulating-air oven for 4 hours at 125° C (257° F) for cure of the resin.

To produce an assembly having a density between the densities of the structures bonded with phenolic glue and those treated with the polyester type of laminating resin, a core assembly was first fabricated as B in table 1. After cure of the bonding adhesive, the core blocks were dipped in an alcohol-soluble phenolic-resin solution to yield treatment C (table 1). When using a 60-percent concentration of the solution, about 30 percent of solid resin was absorbed by the core on the basis of the weight of the treated core after cure of the saturating resin. The saturating resin was cured in the oven at a temperature of 125° C (257° F).

METHODS OF TEST OF BASE SHEET MATERIALS

Physical Properties of Base Material

Thickness, weight, density, porosity, and wet and dry tensile strength tests of the impregnated and of the unimpregnated sheet materials before corrugation were obtained according to the standard methods of the Technical Association of the Pulp and Paper Industry.

Moisture Absorption and Dimensional Stability of Base Sheet Material

For dimensional stability and moisture-absorption determinations on the uncorrugated sheet material, three specimens approximately 6 inches square were cut from the impregnated and from the unimpregnated material. Specimens were exposed at about 30-percent relative humidity for 3 weeks. Dimensional measurements in both the predominant fiber and crossfiber directions were made at this condition with a metal ruler reading accurately to 0.01 inch. Weight measurements were also made at this condition with an analytical balance. Specimens were then exposed to each of the humidity conditions of about 65, 80, 90, and 97 percent for a period of 2 weeks. Weight measurements were made while the material was at each of these conditions, and dimensional measurements were made at the condition of 90-percent relative humidity only. The specimens were then oven-dried for calculation of weight and

dimensional data. The dimensional change was expressed as a percentage of the oven-dry dimension of the sample. The equilibrium moisture content was expressed as a percentage of the weight of the oven-dry specimen.

METHODS OF TEST OF HONEYCOMB CORE MATERIAL

Preparation of Test Specimens

The blocks of honeycomb core materials were cut into test specimens on a band saw having a blade with about 24 teeth per inch and traveling at a rate of 3500 feet per minute. The first cut reduced the L dimension about 3/4 inch and left a surface normal to the axis of the cells. Then several sections 1/2 inch thick in the L-direction (fig. 1) and a section 6 inches in the L-direction were cut. These sections were then cut into specimens 2 by 2 by 6 inches for compression tests, and 2 by 6 inches by 1/2 inch for shear tests in the LT-plane.

Dimensions of the specimens for compression and shear tests were measured before any further preparations; these dimensions were checked immediately before test.

To prepare the specimens for testing, the ends of the compression test specimens were set in molding-plaster casts to a depth of approximately 3/8 inch and dried before conditioning. The plaster caps eliminated localized crushing at the ends of the cells in contact with the heads of the testing machine. For the tension tests, sections of core material 1/2 inch thick in the L-direction had 1-inch aluminum cubes bonded to the ends of the honeycomb cells on each face of the sections of honeycomb core. These tension specimens were prepared in groups of as many as 25 at a time by the use of an alining jig of the type shown in figure 5. A two-part resin adhesive, composed of a polyvinyl-formal powder and a phenol-resin liquid, especially formulated for bonding to metal was used in bonding the aluminum cubes to the honeycomb core. Two medium brush coats of liquid adhesive were applied to the clean face of the aluminum cube 1 hour apart and immediately after the second coat the powdered adhesive was sprinkled into the liquid film with the excess removed by a light tapping. The adhesive was applied to both faces of the core by dipping the core in a 1/16-inch-thick layer of the liquid adhesive and then into a mound of powdered adhesive. The adhesive coating was air-dried overnight, and then the joints were assembled. The bonds were cured between the electrically heated platens of a hydraulic press to which a pressure of 15 psi was applied for 2 hours at 320° F. After the bonding operation was completed the individual specimens were trimmed to a nominal 1- by 1-inch section.

The shear test specimens were bonded between steel plates with the use of special alinement jigs. The procedure used in bonding the steel plates to the cores was the same as that used in bonding the tension specimens, except that the steel plates were cleaned by abrading with emery cloth and washing with ethyl acetate, and the time in the press was reduced to 1 hour because less time was required to heat through the thin plates than through the cubes used for the tension specimens.

Conditioning of Honeycomb Specimens

The prepared specimens to be tested dry were stored in a room maintained at 75° F and 64-percent humidity for a period of at least 10 days to allow them to reach equilibrium conditions.

For wet tests, the prepared specimens were thoroughly wetted in tap water and soaked for at least 24 hours before test. In the preparation of these test specimens, the ends of the cells were closed by either plaster or aluminum cubes. Entrance of the water into the core material was thus retarded, and normal 24-hour-soaking techniques could not be used. Thorough wetting, however, was accomplished by means of the following treatment:

(1) A vacuum of about 26 inches of mercury was slowly drawn, over a period of 1 hour, on an autoclave containing the submerged specimens

(2) Conditions were maintained constant for 1 hour to remove air from the closed cells in the specimens

(3) Air pressure in the autoclave was slowly increased, over a period of 2 hours, to a gage pressure of 15 psi

(4) Pressure was maintained for 1 hour to allow water to penetrate all closed cells

(5) Pressure was slowly reduced, over a period of 1 hour, to atmospheric

After this treatment the specimens remained submerged in water for a period of at least 24 hours before being tested. It was demonstrated, by means of cutting open a frozen specimen, that this treatment at least partially filled all the closed cells with water regardless of the resin content of the material.

Core Test Procedures

All test procedures were in accord with those specified in reference 1.

Compression tests.-Compression tests were made as indicated in figure 6. Specimens were placed on the machined steel plate and loaded through the self-alining fixture in a hydraulic testing machine. Load was applied with the head traveling at a constant rate of about 0.02 inch per minute. The Martens mirror apparatus with a 2-inch gage length was used with the knife edges bearing on the LR surfaces to measure strains. Data recorded included loads and corresponding deformations and the maximum load. Five specimens were tested for each material and for each conditioning treatment.

Tension tests.-Tension tests were made as indicated in figure 7. At each end of the specimen the aluminum cubes were loaded through pin connections to the receptacles on the tension loading rods. The receptacles were also free to rotate about an axis perpendicular to the pin connections; thus the ends were self-alining. The maximum load was obtained for 25 specimens of each material at each condition.

Shear tests.-The shear test is illustrated in figures 8 and 9. Knife-edge ends of the steel loading plates bore on the lower head of a hydraulic testing machine and on a self-alining fixture attached to the upper head of the machine. The dial gage was supported from one plate with the gage spindle contacting a bar supported from the other plate to measure the shear deformation of the core. The data obtained included the loads and the corresponding shear deformations until the straight-line relationship had been exceeded and the maximum load reached. Four specimens were tested for each material.

COMPUTATION OF PROPERTIES

The compressive strength was computed from the compression test data by dividing the maximum load by the cross-section area. The data for load against deformation were plotted, and a straight line was drawn to fit at least the lower portion. The slope of this line was used to compute the modulus of elasticity E by the formula:

$$E = \frac{P}{eA}$$

where P is the load in pounds, A is the cross-section area in square inches, and e is the strain in inches per inch. The five values for each condition were then averaged, and the averages were recorded in tables 2 to 4.

The cell walls in all of the compression test specimens buckled at failure, and most of them started buckling long before the maximum load was reached. Observed strengths tabulated should be attainable or exceeded when the materials are used in sandwich structures.

The strength in tension was equal to the observed maximum load because the cross-section area of the test specimens was 1 square inch. The average was computed for each group of 25 tests and was recorded in the tables 2 to 4.

Tensile strength observed for each material could not be greater than the strength of the bond between the core and the aluminum cubes. Only a few materials had less than 100 percent of the failures occur in the cores. The average percentage of core failure is given in tables 2 to 4 along with the tensile strength. The strength there given for the core should be obtained in sandwich constructions if the bonds between core and facing are adequate.

The shear strength was computed by dividing the shear component of the maximum load by the area of the cross section. The data for load against deformation were plotted, and a straight line was drawn to fit the lower portion. From its slope the modulus of rigidity in shear G was computed by the formula:

$$G = \frac{Pt}{Ad}$$

where P is the shear component of the load in pounds, d is the deformation in inches, t is the thickness of the honeycomb (about 1/2 in.), and A is the area of the cross section. The average was computed for each group of four specimens and was entered in tables 2 to 4.

Failures occurred primarily in the core itself, not in the glue line, for practically all of the specimens tested in shear. The strengths are therefore true strengths of the core materials under the conditions of test. The shear strength of these cores when assembled into sandwich structures should be attained if the bond to facings is adequate.

ANALYSIS OF RESULTS OF TESTS ON HONEYCOMBS

Comparison of the strengths of the different honeycomb materials should not be made at the different specific gravities tested. Since

tensile strengths are proportional to the specific gravity, strengths per unit weight could be used for comparison. However, shear strength is not proportional to the specific gravity in the range where buckling occurs before failure, but it is proportional to specific gravity in the range where buckling stresses do not affect failure (see reference 2). Strengths in compression are not directly proportional to the specific gravity of the honeycomb in any range (see reference 3). Therefore the comparison was made between strengths adjusted to a common specific gravity of 0.10 for all the different honeycombs.

Tensile strengths were adjusted in direct proportion to the specific gravity by the formula:

$$\text{Strength at specific gravity of } 0.1 = \frac{\text{Test strength}}{\text{Test specific gravity}} \times 0.1$$

Shear strengths, as previously mentioned, are directly proportional to specific gravity over only that part of the range in which buckling does not affect failure. When buckling does affect failure, formula (9) from reference 2 $\left(F_{sg} = C \frac{g_a}{rg - g_a}\right)$ applies. To find the point of transition from the buckling to the nonbuckling range for a particular honeycomb core material requires several tests at different specific gravities, and determination of the point was not included in this study. For the small change in specific gravity from test specific gravity to a specific gravity of 0.1, the difference in adjusting strengths by a straight line instead of by the curve of formula (9) was usually less than 5 percent and seldom more than 10 percent. Also, the data presented by Werren and Norris showed that for the kraft-paper honeycomb cores tested in their study the strength varied in direct proportion to specific gravity in the range with specific gravity greater than 0.06. All but one of the honeycombs tested in the study for this report had a specific gravity greater than 0.06. Therefore the shear strengths herein reported were adjusted to a strength at specific gravity of 0.1 by direct proportion by using the same formula as was used for adjusting the tensile strengths.

Compressive strengths were adjusted to a strength at specific gravity of 0.1 by applying formula (11) of reference 3, which is

$$p_s = c\left(\frac{g_a}{rg - g_a}\right)^{2/3}$$

where

p_s strength divided by specific gravity

c a constant

g_a specific gravity of honeycomb

r ratio of distance measured on periphery of a cell, from one crest to next crest of a corrugated sheet, to distance measured in a straight line across cell from one crest to next crest.

g specific gravity of cell-wall material (measured by immersion in mercury)

Each average compressive strength given in tables 2 to 4 was adjusted by first solving for the constant c after substituting in the formula the values measured on the honeycomb. After c was determined for each honeycomb, p_s was computed by using g_a equal to 0.1. Then, multiplying p_s by the specific gravity gave the strength adjusted to specific gravity of 0.1.

These strengths adjusted to specific gravity of 0.1 show which honeycomb materials are the most efficient on a weight basis, and demonstrate the effect of the variables in the fabrication of the honeycombs on the efficiency of the honeycomb structures.

The effect of thoroughly wetting the honeycomb was determined from compressive-strength and tensile-strength data. The percentage of dry strength retained after soaking, as given in tables 2 to 4, should apply to the adjusted strengths as well as to the tested strengths.

The load-deformation data from compression and from shear tests were used only to determine the modulus of elasticity. For most materials these same data are used also to determine the proportional limit. However, in honeycomb materials, local buckling of the cell walls may cause excessive deformation before the proportional limit is reached for the material in the cell walls. Because initial buckling is impossible to detect visually, a reliable differentiation between buckling and proportional limit is extremely difficult, except that buckling well below the proportional limit is evidenced by excessive deformations. A proportional limit for these honeycomb structures was not determined.

DISCUSSION OF RESULTS

Physical Properties of Base Sheet Material

It was considered important to make a rather extensive evaluation of the base sheet materials, both before and after resin impregnation, as this was a convenient way to determine characteristics inherent to the materials and therefore existent in the core structure.

Some physical properties of the base-fiber sheet materials are given in table 5. These fiber webs differ greatly in strength and in the degree of fiber orientation in the two principal directions. The rayon and cotton webs were about 5 times as strong in the principal fiber direction as in the cross direction, but the ratio for the kraft paper was only about 2 to 1. However, the ultimate strength of the paper on a pound-per-square-inch basis was about twice as great as that of the rayon in the machine direction and 5 times as great as that of the rayon in the cross direction. Likewise, the paper was 5 and 10 times as strong, respectively, as the cotton in the machine and cross-machine directions. Although the weight per unit area of all three materials was nearly equal, the densities varied from 0.24 gram per cubic centimeter for the cotton to 0.68 gram per cubic centimeter for the paper.

In addition to strength, the fiber-resin-moisture relationships were studied. The adsorption of water vapor or liquid water by cellulosic-type fiber sheets and the relation of this to strength provides basic data concerning important properties of any honeycomb structure that can be made from the particular material. Previous work on the impregnation of sheets with phenolic resins showed that a considerable effect on the moisture sensitivity of a material was obtainable which depended not only on the resin but also on the method of combining it with the fiber. One effect may be to repel or retard the penetration of liquid water into the fiber to a very high degree, but not to reduce materially the pick-up of water vapor for long-time exposures. Another effect may be to cause the fiber bonds to be permanently strong, even if complete wetting should occur. A third effect may be to cause an actual reduction in the amount of water vapor adsorbed when equilibrium has been reached. The latter effect, for instance, is most important from considerations of dimensional stability or resistance to decay. Previous work at the Forest Products Laboratory and elsewhere has indicated that water-soluble resin deposited in the fiber web from a water solution was likely to give good resin penetration of fiber structure and would yield sheets with high wet strength, stability, and low equilibrium moisture content. This could occur even if the resin added did not give water repellence or rigidity to the structure.

In order to compare the effects of each of the three resins selected on the actual fiber-moisture relationships, one series of treated sheets was prepared in which cotton, rayon, and wood-fiber paper were impregnated with 30 percent of water-soluble phenolic resin, alcohol-soluble phenolic resin, or polyester resin. The treated sheets were exposed to high humidities, and the gain in weight was determined. The dimensional change occurring with moisture change was also measured. These data are given in table 6. The rayon fiber showed the highest moisture adsorption and the greatest dimensional change, and cotton the lowest adsorption and dimensional change. Values obtained from the paper were slightly higher but near those of the cotton. Likewise, the same relationship in moisture absorption existed for the base sheet materials, as shown in figure 10. These adsorption values represent the permanent reduction in moisture adsorption of these fibers caused by the presence of each resin. These reductions do not necessarily define the loss of strength incident to wetting, as shown elsewhere in this report, but they are related to strength loss and possible deterioration of the cellulose due to high moisture conditions.

Data on the expansion of sheets between oven-dry condition and 90-percent relative humidity showed that the treatment with 30 percent water-soluble phenolic resin reduced cross-machine swelling from 1.04 (without treatment) to 0.22 percent for the treated cotton, from 2.02 to 0.42 percent for the paper, and from 5.16 to 2.17 percent for the rayon. Although a considerable reduction in swelling of the rayon was obtained with 30 percent resin, the gross dimensional change of rayon was several times that obtained from cotton and paper.

Fiber sheets impregnated with 30 percent of alcohol-soluble phenolic resin or 30 percent of polyester resin were not protected against water-vapor pick-up as well as sheets containing water-soluble resin (fig. 11). The alcohol-soluble-resin treatment reduced the equilibrium moisture content of all materials but was less effective than the water-soluble-resin treatment. Sheets containing polyester resin actually adsorbed more water vapor than the untreated sheets, a fact that indicated that the resin not only had failed to protect the fiber but also had adsorbed some water vapor itself. It might therefore be concluded that a pre-treatment with water-soluble phenolic resin was important to render the fiber webs less sensitive to moisture and to offer an improved base sheet material for core fabrication. The subsequent treatment with varied types and amounts of other resins could then be chosen chiefly with respect to their effects on strength and structural characteristics.

Properties of Honeycomb Structures

The pretreated corrugated sheets were selected because of their anticipated effect on properties and were assembled into honeycomb structures. In early work (reference 4) a polyester type of resin was used because it yielded high compressive-strength structures. A high resin content was required in order to saturate the sheet and leave sufficient resin on the surface to bond adjacent sheets. For paper this amount was about 55 percent, but for a good bond between corrugated sheets of rayon and cotton it was necessary to use up to 70 percent of resin. Since the fiber is probably the chief component with respect to tensile strength, it seemed desirable to use a minimum of resin as one part of this series. Such a condition was achieved by simply gluing the pretreated corrugated sheets together. A third general condition was obtained by dipping the glued corrugated structure in a solution of alcohol-soluble phenolic resin to produce a stiffer material having an intermediate density.

Effect of fiber orientation.—To permit a comparison of the effects of fiber orientation of the strength properties, tests were made on honeycomb structures in which the principal fiber-grain direction was both parallel (L) and perpendicular (T) to the axis of the cells. These data are given in table 2. A great increase in tensile strength was obtained when the fiber grain was in the L-direction. This was particularly evident in cores made with cotton or rayon webs that had a high degree of orientation. Although the orientation effect in paper was not so great, the tensile strength obtained from a paper structure in which the grain was in the L-direction was greater by a considerable margin than that obtained from either the highly oriented cotton or rayon. The approximate ratio of directional tensile strength of these cores was 2 to 1 for paper and 5 to 1 for cotton and rayon, when all were bonded with a phenolic adhesive. These ratios agree well with tensile values obtained on the base sheet material before corrugation.

The difference in tensile strength representing each of the two principal grain directions was more pronounced for the cores containing the least amount of resin. To expect this is reasonable, since the fiber represents most of the total weight of the core in the case of cores made of pretreated paper only. In the case of the cores bonded with a large amount of polyester resin, much of the weight of the core is that of resin that has no grain and the total grain effect is therefore minimized.

Core structures in which the fiber grain was in the L-direction also yielded higher compressive-strength values than cores in which the fiber direction was in the T-direction. The effect was not so pronounced, however, as that observed in the case of tensile strength. Specimens that had been saturated in water and tested when wet exhibited

a similar pattern with respect to directional effect, but the level of strength was lower. In most cases the percentage of compressive strength retained upon wetting was greater for cores having the grain in the L-direction.

Shear-strength values were determined, but no trend in strength due to fiber-grain direction was apparent.

Effect of base fibrous sheet material.-To determine the effect of the type of fibrous sheet material on properties of honeycomb structures, cores were made from nonwoven rayon, nonwoven cotton, and kraft paper. Strength data on these cores are also given in table 2. The highest values (corrected to a common density) were obtained from the paper-base core material. This was true for tension, compression, and shear tests, both dry and wet. The adjusted tensile strength on dry-paper core material was 1.5 to 2.0 times as great as that obtained on rayon or cotton material, based on a comparison of cores in which the fiber-grain direction was parallel to the flute direction and therefore to the applied load. From a comparison of cores in which the fiber grain was perpendicular to the load, the tensile strength of the paper core was about 3 times as high as that obtained from rayon or cotton cores. Changes of the same order of magnitude were also observed in compression-test results.

The rayon, cotton, and paper were all treated effectively by the resins, as indicated by the results of tests on wet specimens (table 2). The retention of tensile strength following wetting of the specimens was very high, and in several cases the wet strength was higher than the dry tensile strength. The cotton core retained the most of its tensile strength on a percentage basis, and rayon the least, with paper in an intermediate position. Only one core lost more than 25 percent of its tensile strength upon complete saturation. In most cases the cotton cores were appreciably stronger in tension after wetting than they were when dry. However, because of the high original strength of the paper core, its actual values were usually higher than those obtained from cotton or rayon with the same type of impregnation.

The retention of compressive strength of cores upon thorough wetting was not so great as that found for tensile strength. The retention of compressive strength of paper core was from 50 to 76 percent, of rayon core from 27 to 60 percent, and of cotton core from 38 to 100 percent. A comparison of shear strength of dry core material with equivalent resin conditions showed the paper to have shear strengths from 1.25 to 2 times those of cotton or rayon.

One series of cores was made to study the effect of a change in the weight per unit area of the base material. The percentage of resin

was kept constant for comparisons of light and heavy papers. An increase in the weight of paper from 40 to 110 pounds (3000 square feet) did not appreciably alter the tensile strength when adjusted to a specific gravity of 0.1, as shown in table 3. The shear strength also remained reasonably constant when compared at a specific gravity of 0.1. Comparing the actual tensile strengths of the two weights of paper, higher values were obtained with the 110-pound paper than with the 40-pound paper. An actual tensile-strength value higher than 1130 psi could have been realized with the 110-pound paper if a more satifactory glue bond could have been developed between the core and the facing.

Effect of saturating and bonding resins.-The saturation or pretreatment of the cellulose-fiber sheet with water-soluble phenolic resin was selected as a desirable procedure on the basis of considerable previous work on the protection of cellulose against moisture. Strength data on cores made with this pretreated paper alone and without subsequent large treatment with resin showed the pretreatment to be very effective for preventing loss of strength of the structure upon wetting (table 4). The retention of tensile strength upon wetting increased as the pretreating-resin content increased. A retention of more than 50 percent resulted with as little as 2.5 percent resin, and more than 90-percent retention resulted when the resin content was 10 percent or more. It should be noted that a portion of this strength undoubtedly can be attributed to a phenolic glue line that was necessary to hold the sheets together into a structure. The retention of compressive strength upon wetting was not so great and ranged from 28 to 60 percent over the complete resin-content range of 2.5 to 30 percent. This range was based on pretreated material only. This type of treatment therefore appears to be attractive, since it overcomes the inherent great loss of strength of paper upon wetting. The presence of this resin to impart wet strength broadens the possible selection of resins for further impregnation; the secondary resin may be chosen for the special mechanical properties it may give to the structure.

Honeycomb structures were produced by assembly of the pretreated corrugated sheets by using three different resin treatments (table 1). The pretreated paper bonded with phenolic glue produced structures with a higher adjusted dry tensile strength than the other two types of treatment when the fiber grain was in the L-direction. However, cores soaked in the alcohol-soluble phenolic resin had wet-tensile-strength values substantially equal to or greater than the strength of the dry material. The greatest adjusted dry compressive and shear strengths were also obtained with this type of resin treatment. The polyester-resin treatment produced structures with higher density because of the great amount of resin needed to bond the sheets together, and, in general, the adjusted strength values were lower than those obtained with the alcohol-soluble resin.

SUMMARY OF RESULTS

The following results were obtained from tests to determine the effect of fiber type, fiber orientation, resin type, and resin content on the strength properties of honeycomb core structures:

(1) Higher tensile and compressive strengths were obtained in honeycomb structures having the principal fiber grain parallel to the axes of the cells than in those having the fiber grain perpendicular to the axes of the cells. This was true for cotton, rayon, or paper.

(2) Honeycomb structures made from paper had higher dry and wet tensile- and compressive-strength values than structures made from rayon or cotton when comparing cores having the fiber grain either parallel or perpendicular to the axes of the cells. All three materials retained more than 75 percent of their tensile strength upon wetting, and in some cases the wet strength was considerably higher than the dry strength. The cotton structures retained a greater percentage of their dry strength upon wetting than the paper structures, and the rayon retained the least.

(3) Increases in pretreating-resin content of the corrugated paper were more effective in increasing the strength of the structures when tested in the wet condition than in the dry condition, and also for structures made with a small proportion of total resin than with a large proportion of resin.

(4) In general, cores made by using alcohol-soluble-resin treatment had higher adjusted strength values than structures made from the polyester resin or from the pretreated paper only.

(5) A honeycomb structure having high and equally adjusted compressive and tensile strengths was made from 40-pound corrugated paper bonded with a simple glue and having the fiber grain parallel to the axes of the cells.

(6) A core with an actual tensile strength in excess of about 1000 psi and with an actual compressive strength of about 2650 psi was made from 110-pound paper and polyester resin. The specific gravity of this core was 0.234 gram per cubic centimeter.

Forest Products Laboratory
Madison, Wisc., December 22, 1950

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2. Werren, Fred, and Norris, Charles B.: Analysis of Shear Strength of Honeycomb Cores for Sandwich Constructions. NACA TN 2208, 1950.

3. Norris, Charles B.: An Analysis of the Compressive Strength of Honeycomb Cores for Sandwich Constructions. NACA TN 1251, 1947.

4. Norris, C. B., and Mackin, G. E.: An Investigation of Mechanical Properties of Honeycomb Structures Made of Resin-Impregnated Paper. NACA TN 1529, 1948.

TABLE 1.- TYPES OF RESIN TREATMENT

Identification	Pretreatment	Additional treatment
A	Water-soluble phenolic saturating resin (resin 6)	High-temperature-setting, low viscosity, laminating resin of polyester (styrene-alkyd) type with a benzoyl peroxide catalyst (resin 2) used for bonding corrugated sheets together as well as for further impregnating core; paper structures contained 50 percent resin, and rayon and cotton structures contained 70 percent resin
B	-----do-----	Sheets bonded with 10 percent of an intermediate temperature-setting, acid-catalyzed phenol resin with 6-percent catalyst (resin 29) with no further impregnation
C	-----do-----	Sheets bonded with resin 29 and core impregnated with 30 percent of an alcohol-soluble phenolic saturating resin (resin 7)

TABLE 2.- EFFECT OF FIBER ORIENTATION AND BASE SHEET MATERIAL ON PROPERTIES OF HONEYCOMB STRUCTURES

Core	Weight per 3000 sq ft (lb)	Resin content (pretreatment) (percent)	Direction of fiber (1)	Type of resin treatment (g/cc) (2)	Specific gravity of honeycomb (g/cc)	Specific gravity of cell-wall material (g/cc)	Ratio, r	Tension						Compression						Shear		
								Dry			Wet		Strength retention upon wetting (percent)	Dry			Wet		Strength retention upon wetting (percent)	Dry		
								Strength (psi)	Strength adjusted to $g_a = 0.1$ (psi)	Failure in honeycomb (percent)	Strength (psi)	Failure in honeycomb (percent)		Strength (psi)	Strength adjusted to $g_a = 0.1$ (psi)	Modulus of elasticity (psi)	Strength (psi)	Modulus of elasticity (psi)		Strength (psi)	Strength adjusted to $g_a = 0.1$ (psi)	Modulus of elasticity (psi)
5	40	20	T	B	0.063	0.846	1.179	248	394	100	244	100	98	239	531	41.0×10^3	121	14.5×10^3	51	165	262	16.9×10^3
8	40	20	L	B	.062	.847	1.160	497	802	100	425	97	86	303	708	98.4	201	62.4	66	180	290	17.1
6	40	20	T	C	.083	1.095	1.155	335	404	100	351	100	105	526	724	72.9	264	30.9	50	328	395	33.2
9	40	20	L	C	.089	1.124	1.190	486	546	99	517	100	106	611	746	135.5	437	99.0	72	248	279	26.8
4	40	20	T	A	.099	1.279	1.238	484	489	100	411	100	85	566	576	67.5	289	36.0	51	328	332	24.0
7	40	20	L	A	.106	1.307	1.282	549	518	95	519	45	95	766	693	138.1	586	132.6	76	318	300	23.8
20	45	20	T	B	.062	.563	1.168	67	108	100	69	100	103	99	229	13.2	27	3.5	27	91	146	6.0
23	45	20	L	B	.065	.555	1.171	343	528	99	252	100	73	211	451	47.7	79	17.7	37	116	178	7.4
21	45	20	T	C	.083	.731	1.199	154	186	100	156	100	101	176	244	22.1	48	5.9	27	151	182	9.3
24	45	20	L	C	.096	.824	1.183	426	444	100	401	99	94	453	486	62.6	147	19.9	32	216	226	13.8
19	45	20	T	A	.117	1.061	1.235	188	161	100	163	100	87	93	71	9.6	56	6.2	60	292	250	21.5
22	45	20	L	A	.142	1.274	1.279	501	353	100	430	100	86	510	279	76.7	282	34.2	55	277	195	18.1
26	45	20	T	B	.059	.300	1.140	70	119	100	65	100	93	59	158	12.9	32	7.5	54	65	110	6.7
29	45	20	L	B	.059	.395	1.176	353	598	100	375	99	106	144	372	57.4	55	25.3	38	98	166	9.8
27	45	20	T	C	.081	.557	1.190	190	235	100	207	100	109	176	256	34.0	120	23.9	68	99	122	11.1
30	45	20	L	C	.090	.648	1.185	449	499	99	544	---	121	324	390	85.8	256	66.7	79	189	210	15.4
25	45	20	T	A	.149	1.139	1.199	291	196	100	484	94	166	338	169	40.0	230	24.3	68	278	186	20.4
28	45	20	L	A	.158	1.195	1.250	618	392	98	682	74	110	355	161	98.0	470	82.3	132	267	169	27.6

[1] See fig. 1.

[2] See table 1.

TABLE 3.- EFFECT OF WEIGHT OF PAPER ON PROPERTIES OF HONEYCOMB STRUCTURES

Core	Weight of paper per 3000 sq ft (lb)	Resin content (pretreatment) (percent)	Direction of fiber (1)	Type of resin treatment (2)	Specific gravity of honeycomb (g/cc)	Specific gravity of cell-wall material (g/cc)	Ratio, r	Dry tension			Dry compression			Dry shear		
								Strength (psi)	Strength adjusted to $g_a = 0.1$ (psi)	Failure in honeycomb (percent)	Strength (psi)	Strength adjusted to $g_a = 0.1$ (psi)	Modulus of elasticity (psi)	Strength (psi)	Strength adjusted to $g_a = 0.1$ (psi)	Modulus of elasticity (psi)
5	40	20	T	B	0.063	0.846	1.179	248	394	100	239	531	41.0×10^3	165	262	16.9×10^3
14	110	20	T	B	.129	.808	1.247	599	465	100	361	231	84.8	267	207	29.7
6	40	20	T	C	.083	1.095	1.155	335	404	100	526	724	72.9	328	395	33.2
15	110	20	T	C	.179	1.184	1.199	844	472	94	1141	416	172.8	724	405	51.4
4	40	20	T	A	.099	1.279	1.238	484	489	100	566	576	67.5	328	332	24.0
13	110	20	T	A	.217	1.276	1.362	1130	522	51	1754	459	166.5	567	262	46.3
8	40	20	L	B	.062	.847	1.160	497	802	100	303	708	98.4	180	290	17.1
17	110	20	L	B	.110	.823	1.256	820	746	98	486	412	141.6	318	289	36.1
9	40	20	L	C	.089	1.124	1.190	486	546	99	611	746	135.5	248	279	26.8
18	110	20	L	C	.178	1.131	1.229	850	478	76	1222	448	193.8	533	300	55.1
7	40	20	L	A	.106	1.307	1.282	549	518	95	766	693	138.1	318	300	23.8
16	110	20	L	A	.234	1.313	1.374	998	427	4	2655	610	279.9	643	275	78.7

[1]See fig. 1.

[2]See table 1.

TABLE 4.- EFFECT OF RESINS USED FOR PRETREATING AND BONDING OF CORRUGATED PAPER SHEETS ON PROPERTIES OF HONEYCOMB STRUCTURES

Core	Weight per 3000 sq ft (lb)	Resin content (pretreatment) (percent)	Direction of fiber (1)	Type of resin treatment (g/cc) (2)	Specific gravity of honeycomb (g/cc)	Specific gravity of cell-wall material (g/cc)	Ratio, r	Tension						Compression						Shear		
								Dry			Wet			Dry			Wet			Dry		
								Strength (psi)	Strength adjusted to $g_a = 0.1$ (psi)	Failure in honeycomb (percent)	Strength (psi)	Failure in honeycomb (percent)	Strength retention upon wetting (percent)	Strength (psi)	Strength adjusted to $g_a = 0.1$ (psi)	Modulus of elasticity (psi)	Strength (psi)	Modulus of elasticity (psi)	Strength retention upon wetting (percent)	Strength (psi)	Strength adjusted to $g_a = 0.1$ (psi)	Modulus of elasticity (psi)
44	40	2.5	T	B	0.063	0.831	1.090	293	465	100	163	100	56	163	363	33.0×10^3	52	11.0×10^3	32	153	243	19.2×10^3
41	40	5.0	T	B	.056	.752	1.093	283	506	100	178	100	63	131	357	29.7	49	9.5	37	139	248	18.6
38	40	7.5	T	B	.062	.778	1.096	261	421	100	168	100	64	146	335	33.0	61	16.0	42	161	260	22.6
2	40	10	T	B	.057	.802	1.174	230	404	100	212	100	92	122	322	26.5	34	9.6	28	140	246	12.7
5	40	20	T	B	.063	.846	1.179	248	394	100	244	100	98	239	531	41.0	121	14.5	51	165	262	16.9
11	40	30	T	B	.064	.891	1.212	282	441	100	259	100	92	185	398	49.5	111	30.5	60	189	295	19.4
45	40	2.5	T	C	.089	1.060	1.072	494	555	100	370	100	75	426	522	72.0	310	52.5	73	383	430	39.8
42	40	5.0	T	C	.094	1.084	1.090	485	516	100	418	100	86	546	606	73.9	409	63.5	75	352	374	46.2
39	40	7.5	T	C	.099	1.122	1.081	439	444	100	414	97	94	513	523	80.0	337	62.3	66	328	331	37.4
3	40	10	T	C	.087	1.156	1.149	427	491	100	380	100	89	466	590	74.1	410	55.9	88	303	348	30.3
6	40	20	T	C	.083	1.095	1.155	335	404	100	351	100	105	526	724	72.9	264	30.9	50	328	395	33.2
12	40	30	T	C	.086	1.094	1.176	286	333	96	357	100	125	452	586	76.9	245	39.2	54	336	391	31.4
1	40	10	T	A	.083	1.257	1.229	405	488	100	297	80	73	468	644	65.2	295	35.0	63	302	364	20.9
4	40	20	T	A	.099	1.279	1.238	484	489	100	411	100	85	566	576	65.7	289	36.0	51	328	332	24.0
10	40	30	T	A	.099	1.295	1.229	411	415	100	396	100	96	572	582	66.2	443	59.4	77	315	318	22.5

[1]See fig. 1.
[2]See table 1.

TABLE 5.- PHYSICAL TESTS ON UNTREATED AND TREATED PAPER, COTTON, AND RAYON

Material	Type of resin	Approximate resin content (percent)	Weight per 3000 sq ft (lb)	Thickness (mil)	Density (g/cc)	Tensile strength			
						Dry		Wet	
						Machine direction (psi)	Cross machine direction (psi)	Machine direction (psi)	Cross machine direction (psi)
Paper	None	0	42.5	4.0	0.68	11,250	5100	550	295
	Water-soluble phenolic	10	48.2	4.8	.64	10,270	4560	8,960	3810
	----------do----------	20	55.8	5.2	.67	10,500	4720	9,710	4120
	----------do----------	30	59.0	5.5	.69	9,620	4420	8,870	4080
	Alcohol-soluble phenolic	30	58.3	4.4	.85	15,700	7730	10,880	5430
	Polyester	30	53.5	4.2	.84	13,320	6450	2,930	1700
Cotton	None	0	40.7	11.0	0.24	2,010	450	770	130
	Water-soluble phenolic	30	54.5	13.0	.27	3,220	860	2,580	760
	Alcohol-soluble phenolic	30	57.0	12.0	.34	3,590	1100	2,370	170
	Polyester	30	56.6	12.6	.29	2,780	850	760	140
Rayon	None	0	41.0	8.5	0.31	5,070	890	1,940	240
	Water-soluble phenolic	30	62.5	10.5	.38	5,170	1440	2,990	930
	Alcohol-soluble phenolic	30	57.5	8.7	.42	5,170	1410	2,510	600
	Polyester	30	63.2	9.0	.45	4,980	1290	2,150	280

TABLE 6.- EQUILIBRIUM MOISTURE CONTENT AND DIMENSIONAL STABILITY OF UNTREATED AND TREATED PAPER, COTTON, AND RAYON UPON EXPOSURE TO VARIOUS RELATIVE HUMIDITIES

Material	Type of resin	Approximate resin content (percent)	Moisture content based on oven-dry weight of specimen (percent)					Dimensional change (percent) (1)			
			Relative humidity (percent)					Machine direction		Cross-machine direction	
								Relative humidity (percent)			
			30	65	80	90	97	30	90	30	90
Paper	None	0	4.5	8.5	12.1	15.7	31.9	0.53	0.70	1.19	2.02
	Water-soluble phenolic	10	4.2	6.2	8.5	11.0	14.5	.02	.17	.18	.73
	----------do----------	20	3.1	4.6	6.2	8.0	10.1	.03	.07	.08	.50
	----------do----------	30	3.2	4.5	5.9	7.3	8.8	.00	.15	.12	.42
	Alcohol-soluble phenolic	30	4.3	6.5	8.7	11.3	16.5	.33	.50	.74	1.24
	Polyester	30	7.3	9.5	11.9	16.1	29.8	.50	.67	1.06	1.83
Cotton	None	0	5.0	7.8	10.0	13.6	20.8	0.38	0.50	0.52	1.04
	Water-soluble phenolic	30	2.4	3.4	4.6	6.2	7.3	.03	.03	.05	.22
	Alcohol-soluble phenolic	30	3.5	4.8	6.3	8.1	10.8	.02	.17	.18	.43
	Polyester	30	4.9	7.1	8.8	11.0	18.1	.22	.35	.32	.82
Rayon	None	0	7.8	12.3	17.1	23.8	39.4	5.12	4.82	2.63	5.16
	Water-soluble phenolic	30	4.8	7.0	9.8	13.0	16.4	1.06	1.51	1.11	2.17
	Alcohol-soluble phenolic	30	5.6	9.1	12.1	16.3	24.2	2.35	2.82	1.85	3.54
	Polyester	30	7.9	11.3	14.3	18.3	30.6	3.71	4.21	1.66	4.79

[1]Change in dimensions caused by subjecting material to the indicated relative humidity and then oven-drying. Percent change based on oven-dry dimensions.

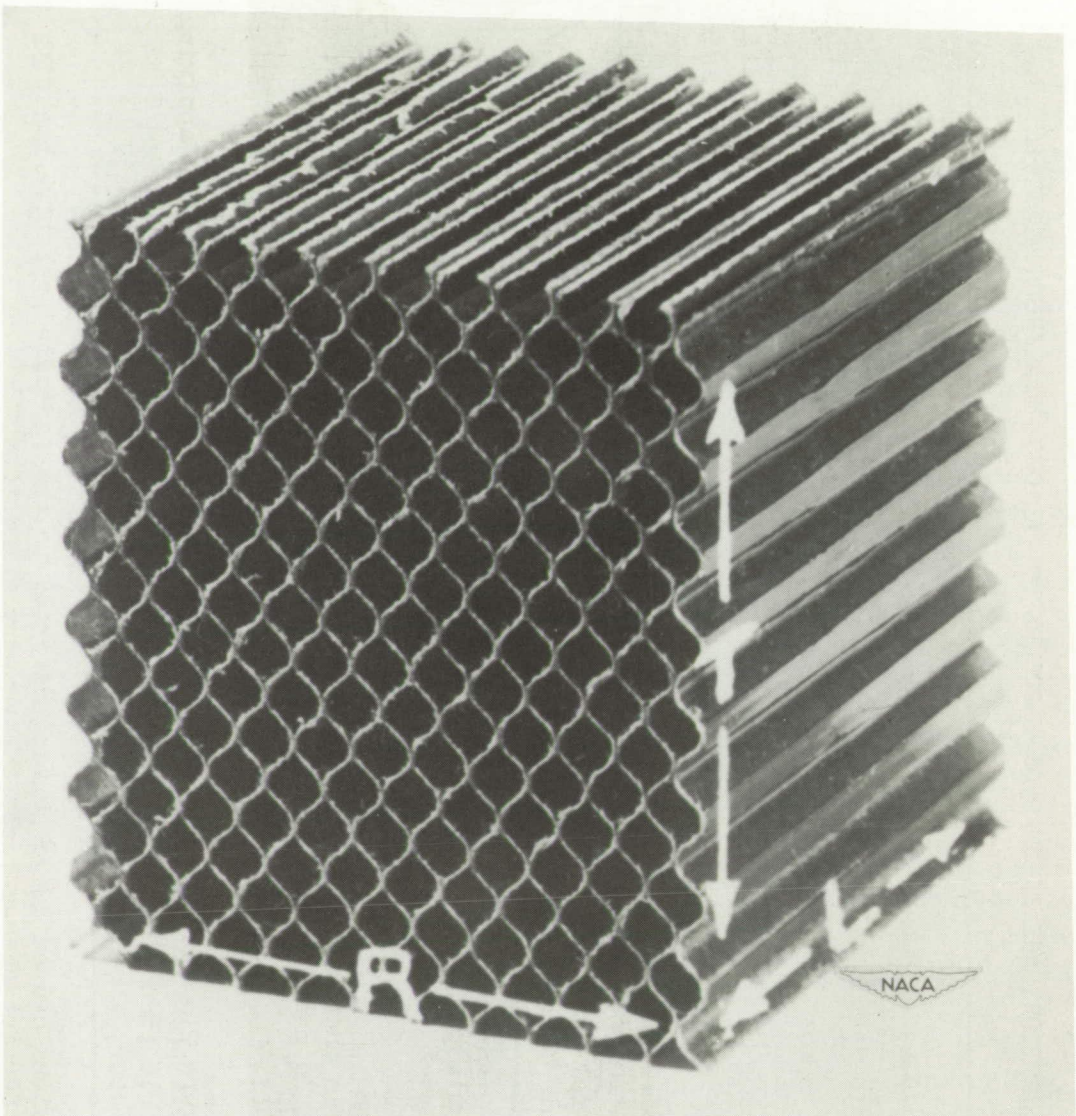

Figure 1.- Cross-sectional view of honeycomb core material showing directional notation as used in report.

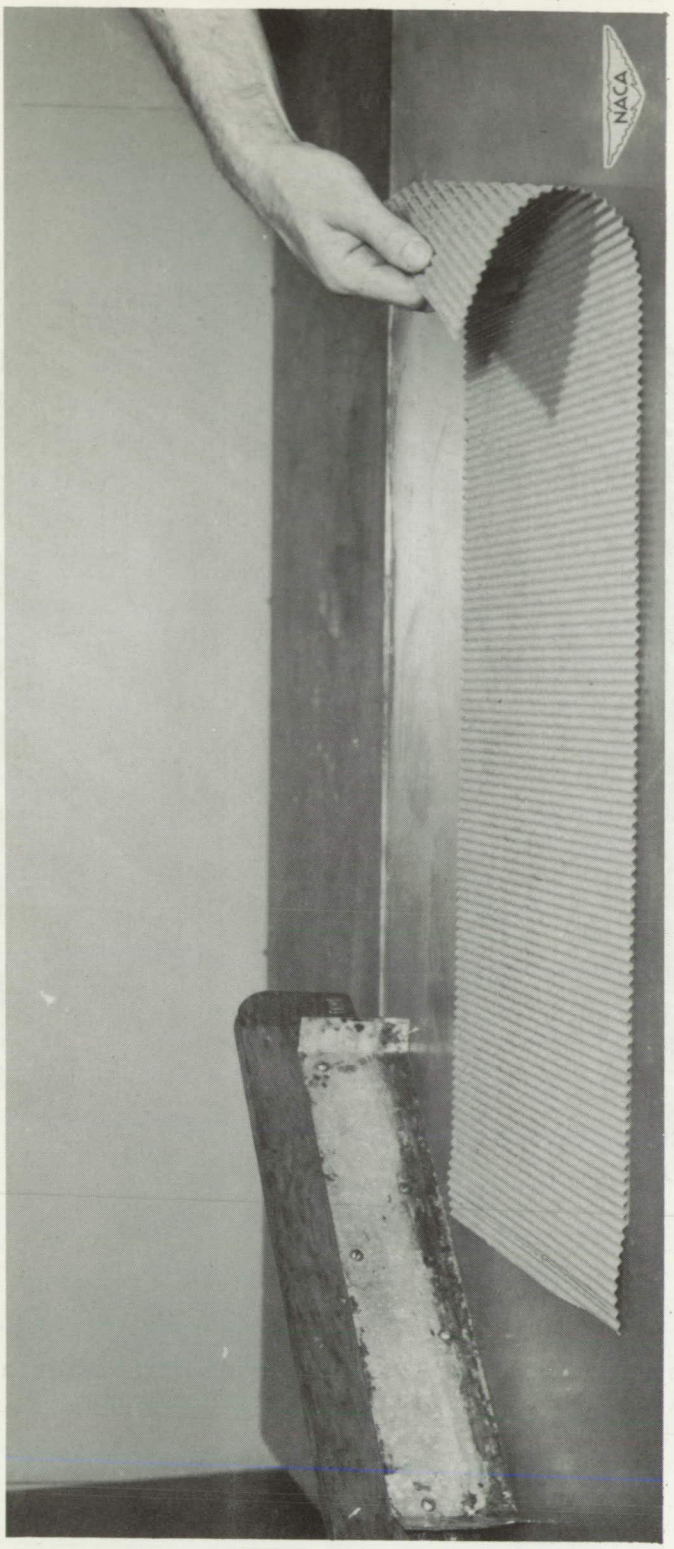

Figure 2.- Plate-glass surface and adjustable doctor blade for applying resin to corrugated paper for resin treatment A.

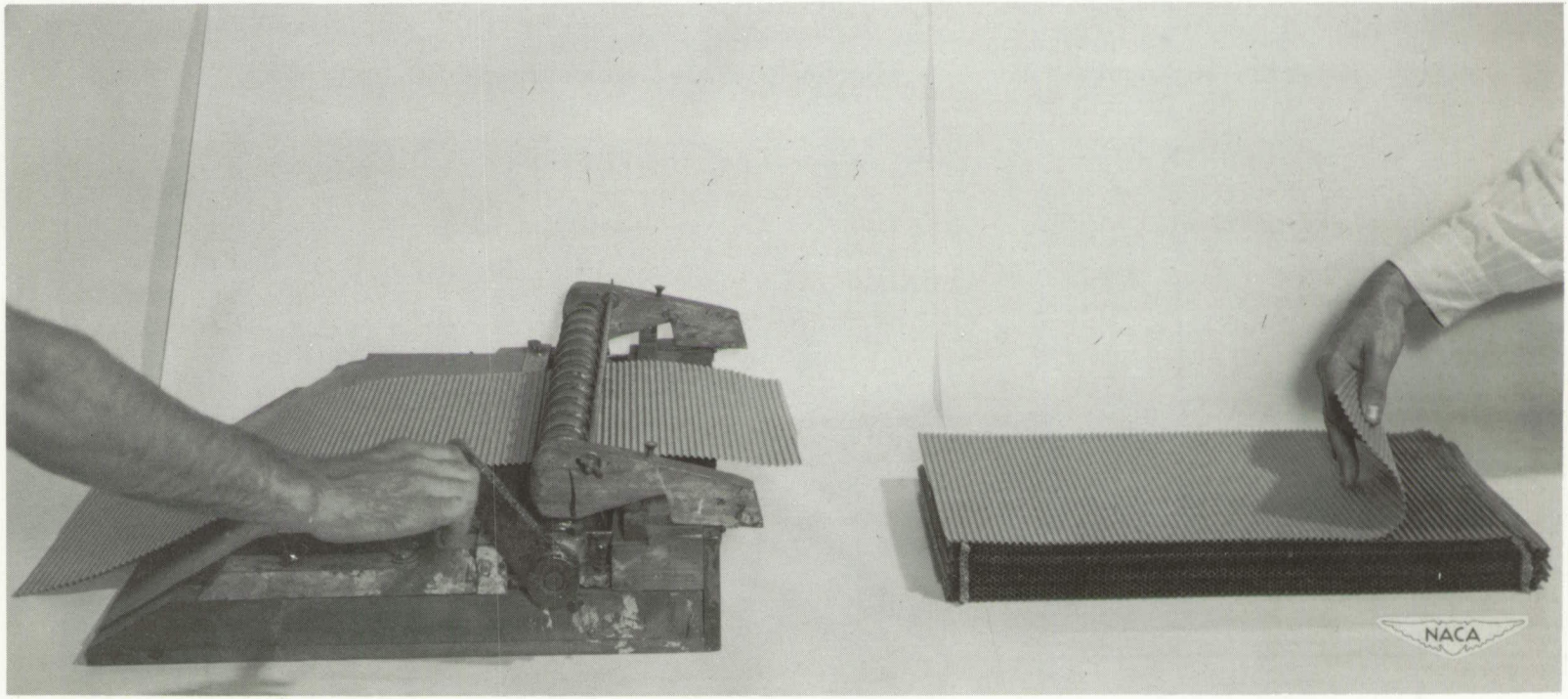

Figure 3.- Left, hand-driven glue spreader used to apply resin treatment B to corrugated sheet. Right, assembly of sheets to make core material.

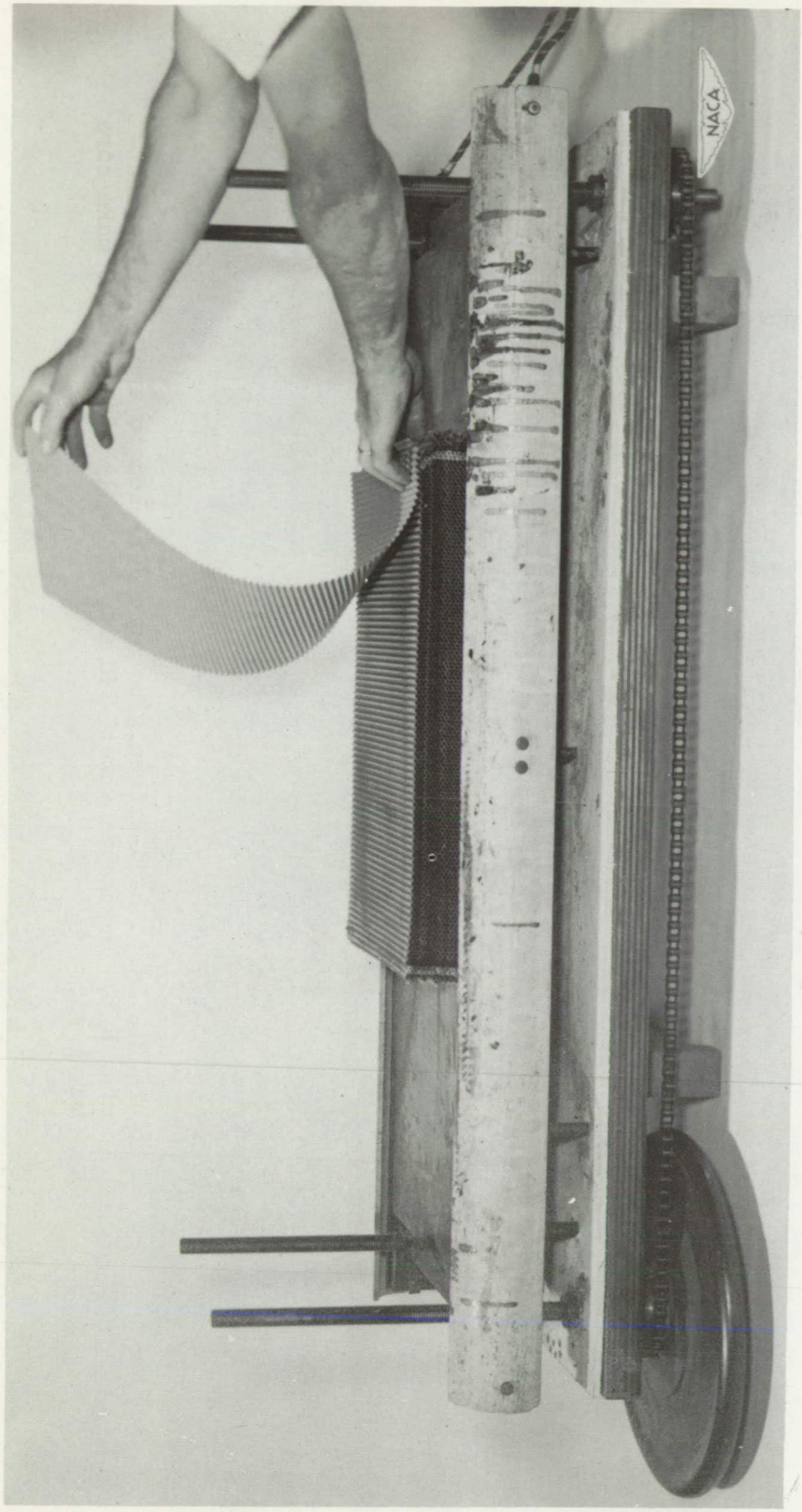

Figure 4.- Jig with strip heaters for maintaining crest-to-crest alinement of corrugated material for resin treatment A. Strip heater hardens resin at edge of blocks to facilitate further handling of sheets and block.

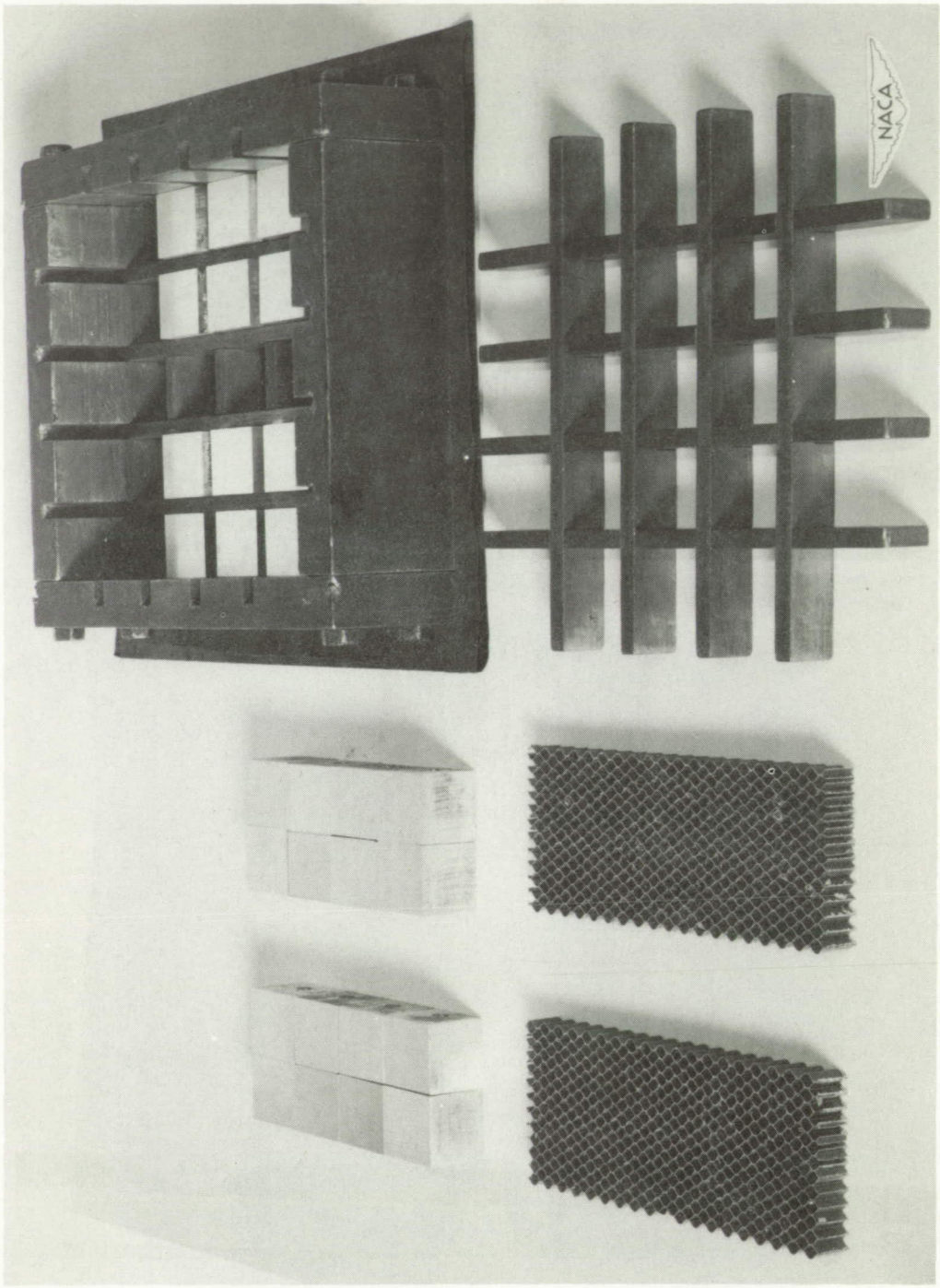

Figure 5.- Alinement jig used in fabrication of 25 or less flatwise tension specimens.

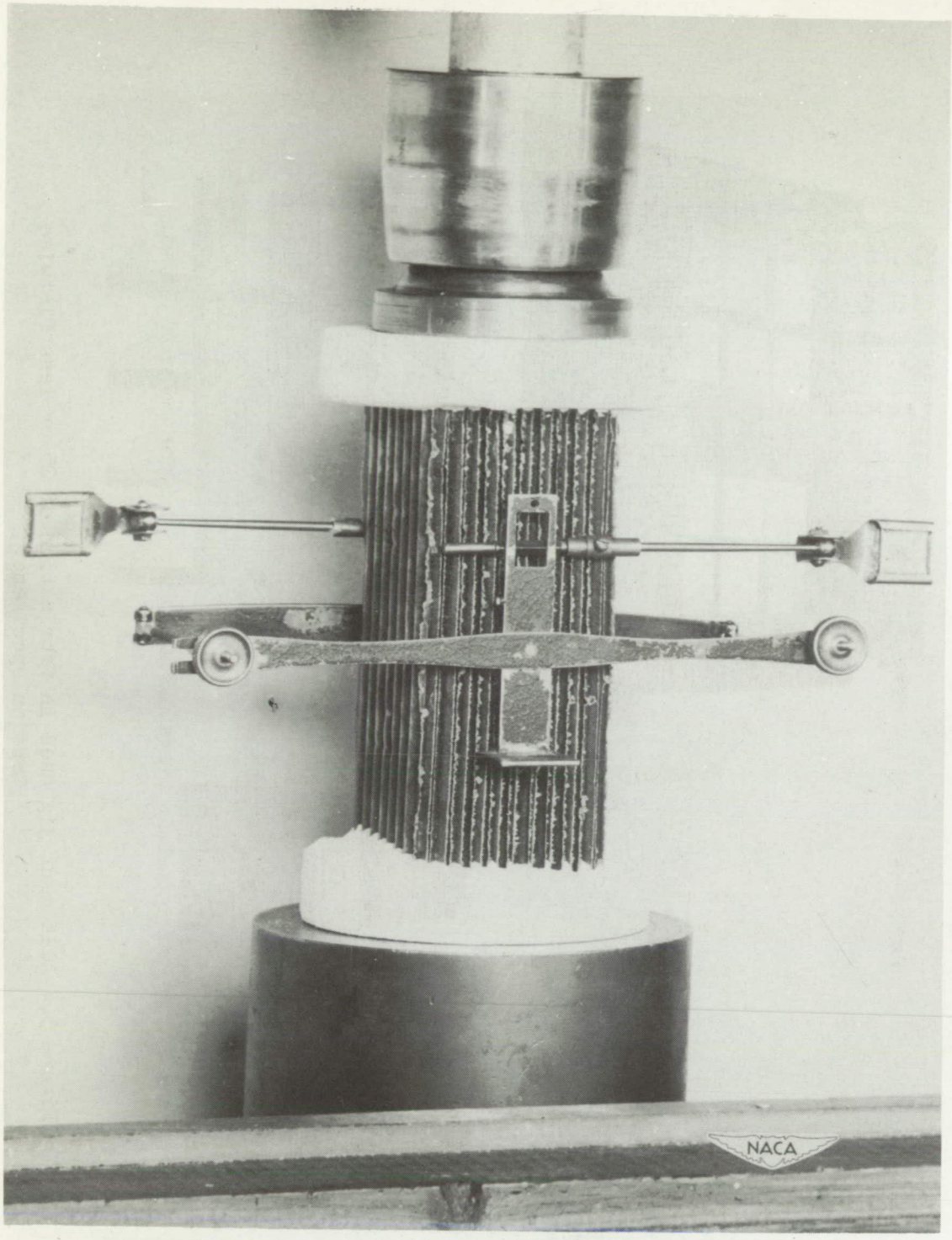

Figure 6.- Compression test of honeycomb core material showing method of providing additional end support at bearing surface through use of cast molding-plaster caps. A Martens mirror-type compressometer is attached to specimen for obtaining deformation readings.

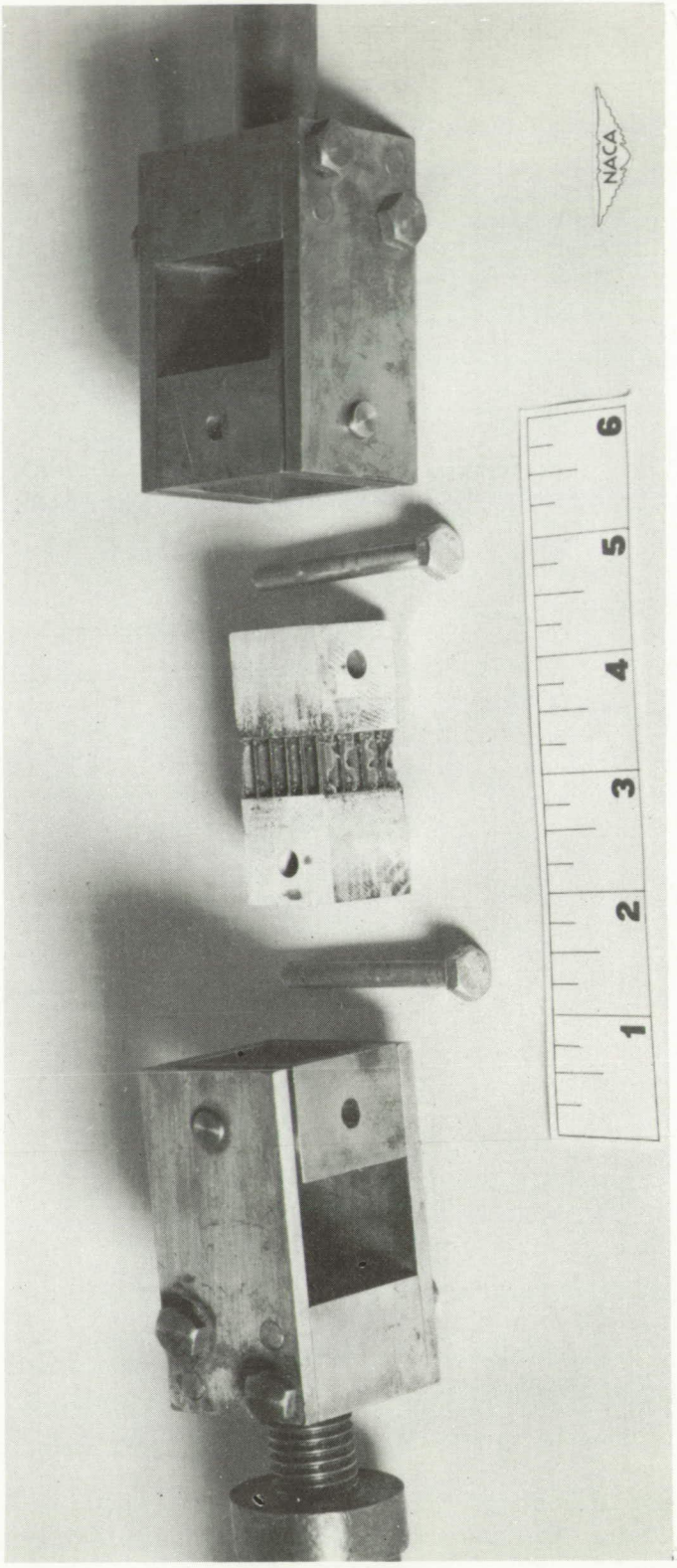

Figure 7.- Specimen and fittings for applying load for tension flatwise tests.

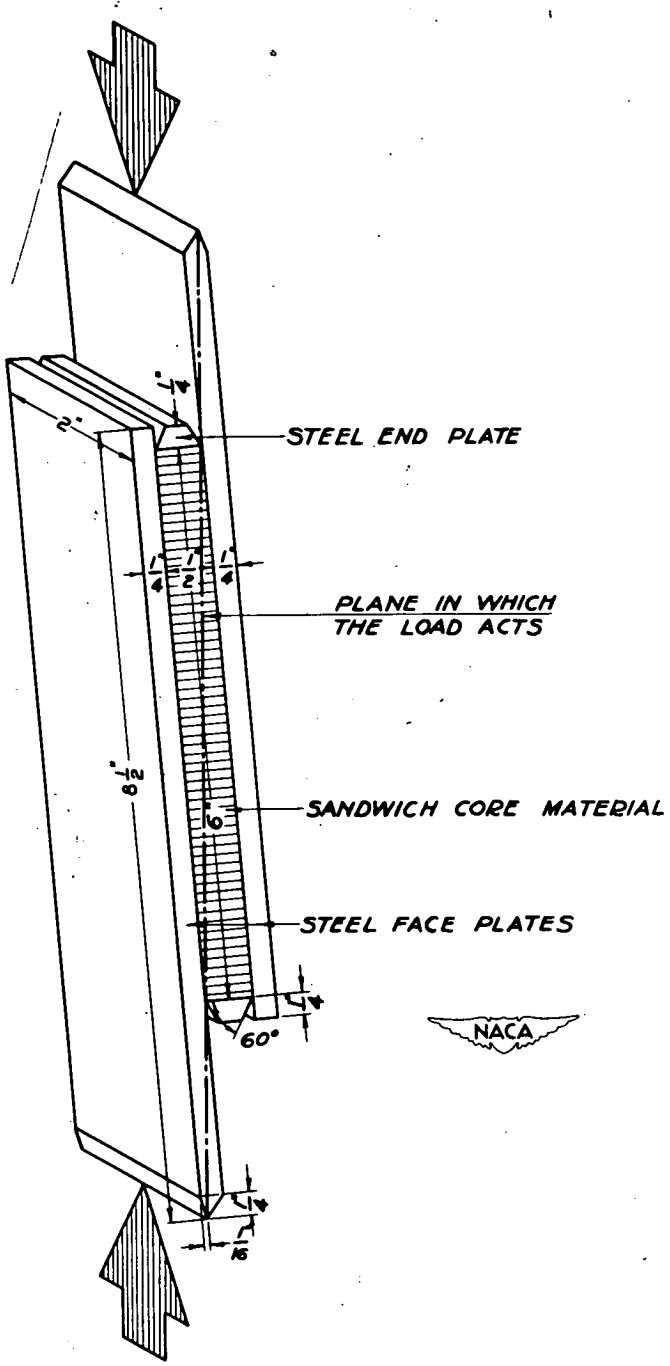

Figure 8.- Shear test specimen of honeycomb material.

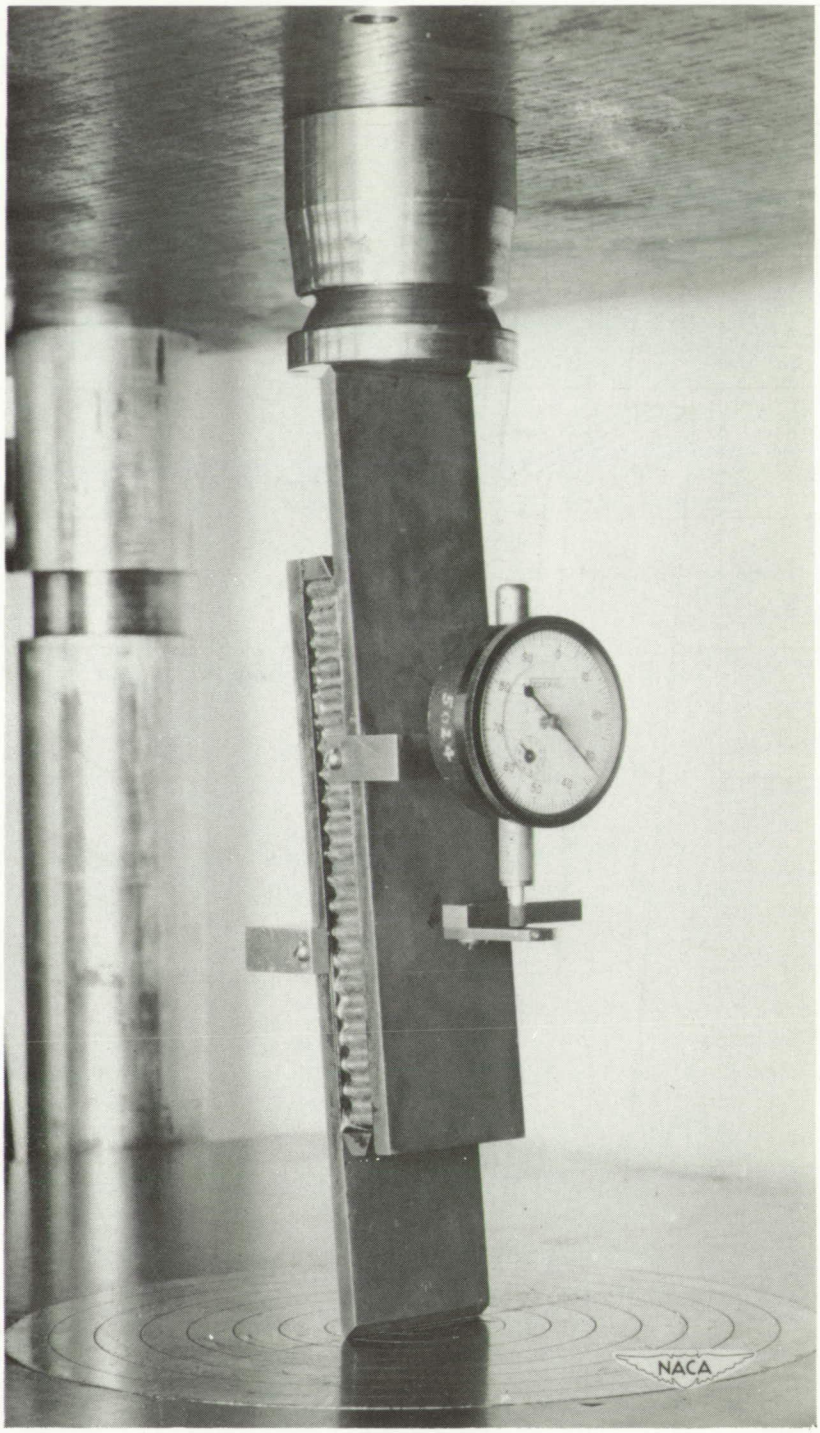

Figure 9.- Apparatus for shear test showing steel plates, specimen, and dial arrangement for measuring deformations between plates.

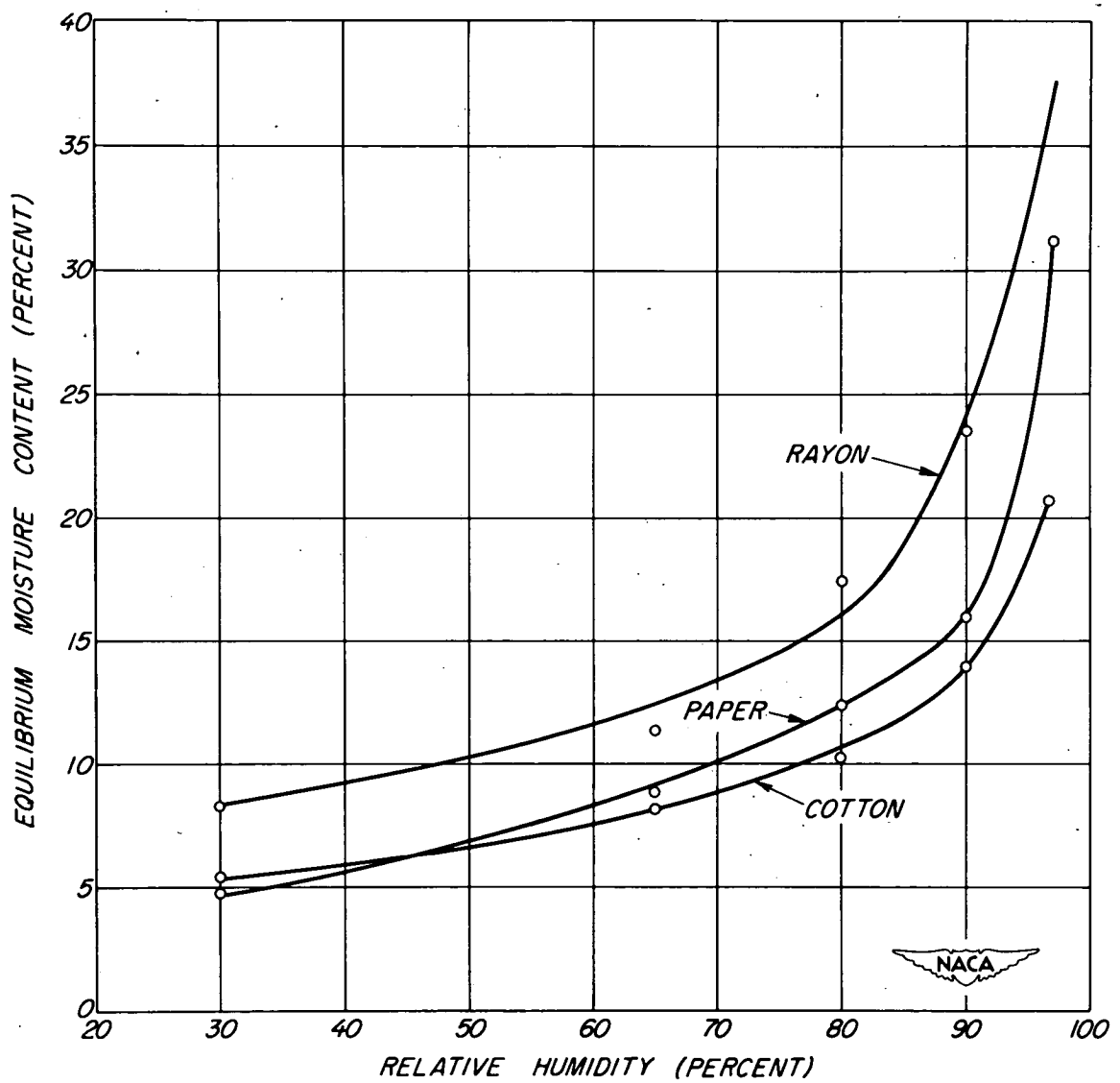

Figure 10.- Equilibrium moisture content of base sheet materials (no resin) after exposure to different relative humidities.

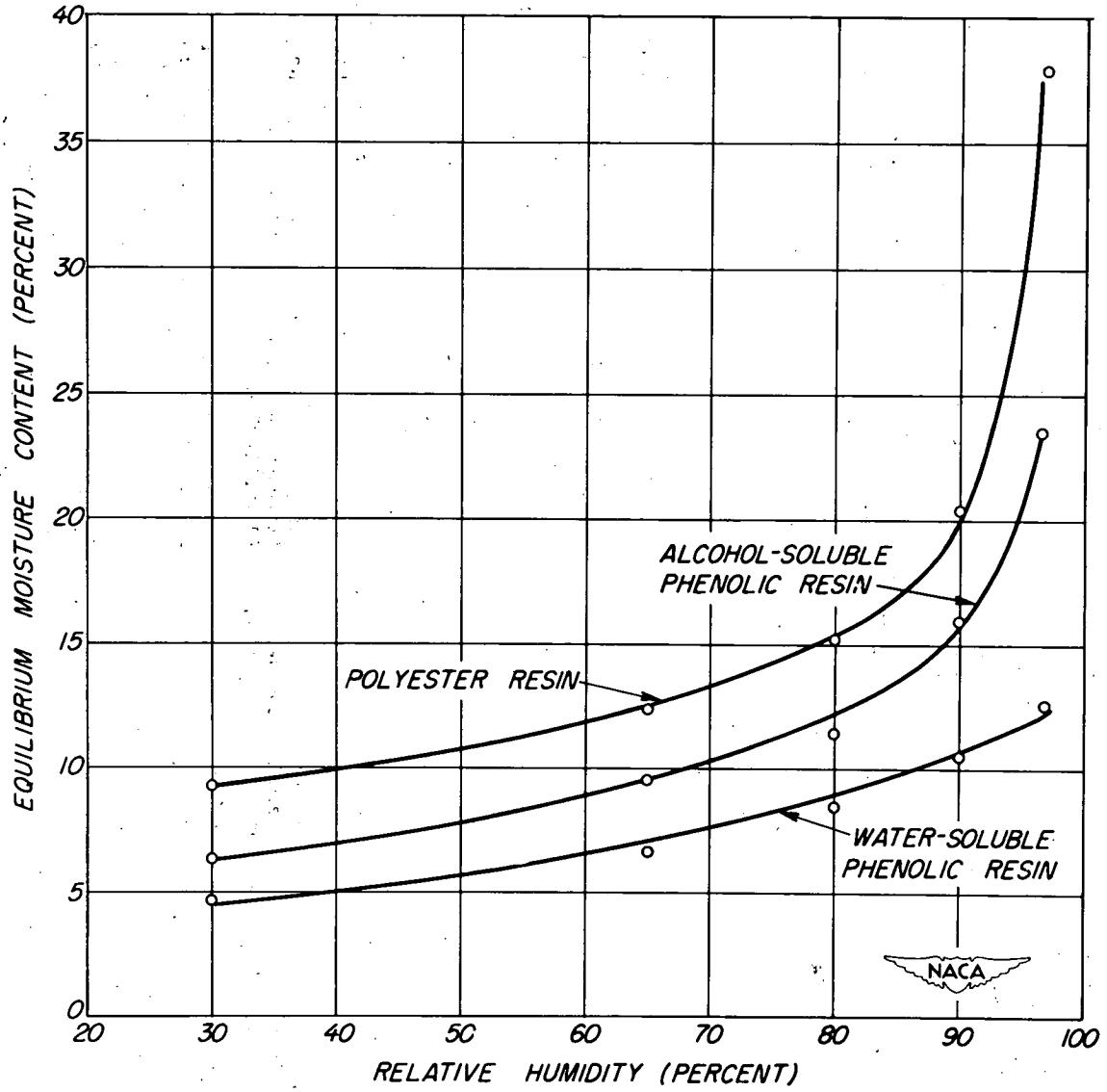

Figure 11.- Effect of 30 percent of various types of resins on equilibrium moisture content of treated paper after exposure to different relative humidities.

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